Microbial Composting of Rice Straw for Improved Stability and Bioefficacy

Hossain Kausar, Mohd. Razi Ismail, Halimi Mohd Saud, Zulkarami Berahim, Sheikh Hasna Habib, Radziah Othman, and Saikat Hossain Bhuiyan

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H. Kausar • M.R. Ismail (✉)
Laboratory of Food Crops, Institute of Tropical Agriculture, Universiti Putra Malaysia,
Serdang 43400, Selangor, Malaysia

Department of Agroforestry and Environmental Sciences, Faculty of Agriculture,
Sher-e-Bangla Agricultural University, SB Nagor, Dhaka, Bangladesh
e-mail: razi@upm.edu.my

H.M. Saud
Laboratory of Food Crops, Institute of Tropical Agriculture, Universiti Putra Malaysia,
Serdang 43400, Selangor, Malaysia

Z. Berahim
Laboratory of Food Crops, Institute of Tropical Agriculture, Universiti Putra Malaysia,
Serdang 43400, Selangor, Malaysia

Oil Seed Research Center, Bangladesh Agricultural Research Institute,
Joydebpur, Gazipur, Bangladesh

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Abstract Rice is an important cereal crop in the world. Annually, a large amount of straw is produced as by-product from rice cultivation. Proper disposal of rice straw is a concern across the world due to its bulk volume. Composting is an alternative way for recycling of rice straw into a valuable end product for agricultural use. However, composting of rice straw is time consuming as it is composed of lignocellulosic material. Therefore, the aim of this chapter is to summarize the pioneering and recent composting studies and provide information about the uses of potential lignocellulolytic microorganisms in composting as an alternative method for sustainable management of rice straw. In addition, the role of rice straw composts in maintaining of soil health, plant growth promotion and disease suppression as bioenhancer and bioprotectant is discussed. This knowledge could help build a platform for researchers in this area to understand the recent developments in rice straw composting by means of addressing the environmental pollution concerns as well.

Keywords Rice straw • Bioconversion • Lignocellulolytic • Growth enhancer • Bioprotectant

1 Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops in the world, with approximately 87 % currently grown in Asia. Rice is the crop that has shaped the diets, cultures, and economics of billions of Asians. For them, rice is more than food, rice is life. Approximately 120,000 varieties are grown across the world in a wide range of climate, water, and soil conditions (Raboin et al. 2014).

The disposal of rice straw is a problem, as it takes up a large area due to its low bulk density, and harbors pests and diseases. Rice straw cannot be used as animal

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S.H. Habib
Senior Scientific Officer, Oil Seed Research Center, Bangladesh Agricultural Research Institute, Joydebpur, Gazipur, Bangladesh

R. Othman
Laboratory of Food Crops, Institute of Tropical Agriculture, Universiti Putra Malaysia, Serdang 43400, Selangor, Malaysia

Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, Serdang 43400, Selangor, Malaysia

S.H. Bhuiyan
Soil Science Division, Bangladesh Institute of Nuclear Agriculture, Mymensingh, Bangladesh

feed due to its low digestibility, high lignin and silica contents which lead to low animal production (Van Soest 2006). Recycling of straw in the field is not feasible because of its slow decomposition rate. In addition, rice straw adds large organic carbon, which leads to net immobilization of nitrogen in soil and the succeeding crops undergo nitrogen deficiency, resulting in lower yield. In Malaysia, a large portion of rice straw is disposed of by open-field burning which causes serious environmental problems. The burning of rice straw emits smoke and dust particles that are harmful to human health, causing asthma and other respiratory problems. It also emits greenhouse gases, namely CO_2, CH_4, and N_2O. Global warming has adverse effects on world climate such as the increase in global temperature, rising water table, melting icebergs, unpredictable weather patterns, and increasing pest infestation and diseases (Gadde et al. 2009; Chang et al. 2013). Attention has to be given to environmentally friendly, nonhazardous, and sustainable methods for proper management of rice straw in a short period of time.

Composting is a promising alternative for the recycling of rice straw (Sanchez-Monedero et al. 2002; Yu et al. 2007; Mishra and Nain 2013; Sharma et al. 2014; Hottle et al. 2015). Composting has long been recognized as one of the environmentally friendly and cost effective alternatives for organic waste recycling (Sanchez-Monedero et al. 2002). Compost is a valuable asset to farmers due to their local availability as a source of multiple plant nutrients (Khaliq et al. 2006). It improves soil characteristics by lowering bulk density, increasing cation exchange capacity, water-holding capacity, soil aeration, buffering capacity, and infiltration rates.

Recent researches have shown that composts suppress plant diseases caused by soil-borne pathogens (Yu et al. 2015; Wei et al. 2015). Composts suppress phytopathogens through various complex biological and physiochemical characteristics (Wei et al. 2015; Ullah et al. 2015). The physiochemical properties reduce disease severity by affecting the growth of pathogen or host plant, while the biological characteristics include the antibiotic production, lytic and other extracellular enzyme production, induction of host-mediated resistance in plants, competition, parasitism, and predation, and other interactions between beneficial microorganisms and pathogens that decrease the disease incidence. Compost sterilization reduces or eliminates disease suppressiveness and colonization by the diverse range of microorganisms resulted in enhanced suppressiveness of diseases (Reuveni et al. 2002; Noble and Roberts 2004; Yogev et al. 2006; Faheem et al. 2015).

One of the imperative aspects of compost application is the degree of maturity and stability. Immature compost may produce phytotoxic effects or enhance anaerobic conditions. Maturity refers to the degradation of phytotoxic compounds produced during the early phases of composting and the proportion of stable humus in compost (Wu et al. 2000; Makan 2015). An optimum level of maturity is attained when compost is stable, but active enough to sustain microbial activity when applying as a biocontrol agent for the control of phytopathogen. Compost maturity and stability are also influenced by the structure and composition of organic materials, and the potential of microbes which decomposed the macromolecules in the substrates.

Phytotoxic compounds are accumulated during composting of lignocellulosic rice straw as it decomposes slowly (Jurado et al. 2015). However, humification process is fed by the intermediate metabolites generated from the bioprocess (Perez et al. 2002). Hence, the successes of composting as well as the usefulness of compost as an organic amendment are highly dependent on the ability of microorganisms. Though, the natural microbial population in rice straw can perform the composting, the inoculation with lignocellulolytic microorganisms could be a strategy that perhaps enhances the bioprocess (Elorrieta et al. 2002; Jurado et al. 2015). In addition, composts need to be colonized by a specific antagonist during the composting process to prepare specific disease suppressive composts (Blaya et al. 2013). As, for example, inoculation of compost with fungal antagonists *Trichoderma viride* gave fruitful results in suppressing *Sclerotium* root rot in chilli (Kausar et al. 2014).

The above information implies that composting of rice straw through inoculation with lignocellulolytic antagonists at optimum conditions might be a promising technique for producing disease suppressive compost in a short period of time. The composting process of rice straw inoculated with lignocellulolytic bioenhancer and its uses for crops have not been widely investigated. Therefore, in the present chapter we integrate different methods of microbial composting of lignocellulosic rice straw and their efficacy in enhancing plant growth and disease suppression as well as in maintaining soil fertility.

2 Production and Properties of Rice Straw

2.1 Rice Straw Biomass

Global rice production was 741.3 million tons in 2014 (USDA 2015). Approximately ~1.5 t straw remains in the field as residue for every ton of harvested grain. Thus, nearly 740–1110 million tons of straw are accumulated annually as a by-product.

Table 1 Rice production of ten leading rice producing countries in the world in 2013 (Statista 2014)

Number	Country	Rice production (Million metric tons)
1	China	203.61
2	India	159.2
3	Indonesia	71.28
4	Bangladesh	51.5
5	Vietnam	44.04
6	Thailand	36.06
7	Myanmar	28.77
8	Philippines	18.44
9	Brazil	11.78
10	Japan	10.76

Table 2 Chemical composition of rice straw (Garay et al. 2014; Kausar et al. 2010; Liu et al. 2013)

Parameters	Rice straw
Cellulose (%)	42–49
Hemicelluloses (%)	23–34
Lignin (%)	11–16
Ash (%)	15–20
Silica (%)	9–14

The world's leading rice producing country is China followed by India. A list of 10-top leading rice producing countries is presented in Table 1.

2.2 Properties of Rice Straw

Rice straw is a complex and highly heterogeneous lignocellulosic material consisting of nodes, internodes, leaves and chaff. It contains three major components, namely cellulose, hemicelluloses, and lignin (Table 2). Cellulose and hemicelluloses are nonlinear and lignin is a three-dimensional polymer (Perez et al. 2002). Cellulose is surrounded by a matrix of hemicelluloses and lignin.

2.2.1 Cellulose

In nature, cellulose is the most abundant linear biopolymer. It comprises approximately 35–45 % dry weight of rice straw (Lynd et al. 2002). It acts as structural and energy-storage components and provides rigidity to the cell wall. In cellulose, glucose unit linked by β-1, 4-glycosidic bonds. Its degree of polymerization can be up to 15,000 units. Each repeating glucose unit is rotated 180° relative to its neighbors. It is classified according to different intermolecular hydrogen bonding patterns as α (insoluble in 17.5 % NaOH) and β (soluble in 17.5 % NaOH) cellulose (Kuhad et al. 1997).

2.2.2 Hemicelluloses

Hemicelluloses are the second largest natural biopolymer after cellulose. It comprises of over 30 % of dry matter in rice straw. It is a branched biopolymer of low molecular weight sugar where the degree of polymerization ranges from 80 to 200 units. Hemicelluloses consist of different sugar units such as xylose, arabinose, glucose, galactose, mannose, rhamnose, fructose, and various methylated neutral sugars. It is amorphous in nature and degraded more easily than cellulose (Perez et al. 2002). Naturally, it remains chemically associated or cross-linked to other biopolymers such as cellulose, lignin, proteins, and pectin. Besides, hemicelluloses form a matrix in primary cell wall together with pectin and protein as well as with lignin in secondary cell wall of rice plants (Hammel 1997).

2.2.3 Lignin

Lignin is the most abundant aromatic biopolymer in the biosphere. It ranges from 5 to 30 % of plant dry weight in lignocellulosic materials (Lynd et al. 2002). It is a high-molecular mass, water-insoluble, three-dimensional compound consisting of phenylpropane-based monomeric units. Its complicated structure, high molecular weight, and non-hydrolyzable bonds make lignin highly resistant to biodegradation. Oxidative enzymes catalyze the biodegradation of lignin. Lignin provides mechanical support, strengthens the cell in vascular tissues, and protects cellulose and hemicelluloses from biodegradation by reducing the surface area available to enzymatic attack. It also plays a role as an antioxidant, as a water-proofing agent ,and as a UV stabilizer (Duval and Lawoko 2014).

2.2.4 Other Cell Wall Components

Besides cellulose, hemicelluloses, and lignin, rice straw also contains silica, terpenes, resins, phenols, low molecular weight carbohydrates, gums, alkaloids, and other chemicals. Carbonates, oxalates, fat, starch, pectin, protein, and various other cytoplasmic constituents are found in the cell wall of straw. These extraneous materials provide a shield against the biodegradation of straw (Kuhad et al. 1997; Lee et al. 2015).

3 Biodegradation of Lignocellulosic Materials in Rice Straw

3.1 Biodegradation of Cellulose

A large number of microorganisms produce cellulolytic enzymes on lignocellulosic materials. Both cellulolytic and non-cellulolytic microorganisms establish synergistic relationship to break down the cellulose during the biodegradation of lignocellulosic materials. The biodegradation of cellulose requires the production of either free or cell-associated extracellular cellulases. The biochemical analyses of cellulose systems from aerobic and anaerobic microorganisms performed during the past two decades have revealed that multiple enzymatic activities are required to hydrolyze cellulose into soluble sugar monomers (Zhang and Lynd 2004; van Zyl et al. 2007; Hasunuma et al. 2013). Three major cellulase enzymes take part during the biodegradation of cellulose. These include endo-1,4-β-D-glucanase, cellobiohydrolase (exo-1,4-β-D-glucanase) and 1,4-β-D-glucosidase. Endoglucanase randomly cleaves the glycosidic bonds of internal amorphous regions in cellulose to produce oligosaccharides of various degrees of polymerization and generate new chain ends. Cellobiohydrolase acts on the non-reducing end of the cleaved cellulose chain and removes cellobiose units from cellulose chains. Finally β-glucosidase acts on cellobiose and converts it into glucose units. The correct combination of the activities and production level of each cellulase enzyme is critical for efficient cellulose bioconversion (Chandel et al. 2012).

3.2 Biodegradation of Hemicelluloses

Hemicelluloses are a heterogenous group of branched and linear polysaccharides that are bound via hydrogen bonds to the cellulose microfibrils in the plant cell wall. They are covalently attached to lignin, forming a highly complex structure together with cellulose. Hemicelluloses require the synergistic action of hemicellulases enzymes for its complete degradation. Hemicellulases are modular proteins, in addition to their catalytic domains, include other functional modules. The most important modules are carbohydrate-binding modules, which facilitate the targeting of the enzymes to the insoluble polysaccharides, and dockerin modules that mediate the binding of the catalytic domains via cohesin-dockerin interactions, either to the microbial cell surface or to large enzymatic complexes (Bourne and Henrissat 2001; Shallom and Shoham 2003). The catalytic modules of hemicellulases are either glycoside hydrolases that hydrolyze glycosidic bonds and carbohydrate esterases, which hydrolyze ester linkages of acetate or ferulic acid side groups. Xylanases are the best studied hemicellulase enzymes. Endoxylanases and xylosidases found in *Trichoderma* spp. and *Aspergillus* spp. can completely breakdown xylan polymers. Endoxylanases cleave the backbone of xylan into smaller oligosaccharide xylobiose, which is further broken down to xylose by xylosidases (Malherbe and Cloete 2002).

3.3 Biodegradation of Lignin

Lignin-degrading mechanisms are extracellular and unspecific as lignin is a large and highly branched biopolymer. Oxidative enzymes cleave stable ether and carbon–carbon bonds in lignin (Yang et al. 2013). The most important lignin-modifying enzymes are lignin peroxidases, manganese peroxidases, functional hybrids of both enzymes (versatile peroxidases VP) and laccases (phenol oxidases). All extracellular peroxidases and laccases catalyze oxidation reactions resulting in the formation of radicals that initiate several spontaneous reactions. These enzymes use low molecular mass mediators during lignin biodegradation which cleave various bond cleavages including aromatic ring fission (Kirk and Farrell 1987; Zeng et al. 2013) in lignocellulosic materials.

4 Composting of Rice Straw

Composting is the bioconversion of organic materials under moist, self heating, and aerobic conditions. It is characterized by a series of different microbial populations. There are a few main factors affect the composting process: temperature, C/N ratio, aeration, moisture content, porosity, and pH (Table 3). Temperature, pH, and nutrients change constantly during composting (Ryckeboer et al. 2003). It reduces the bulk volume of organic materials, destroys weed seeds and pathogenic microorganisms in the end product (Bernal et al. 2009). Typically composting results in a 25–35 % weight reduction of the starting materials. This weight loss is due to the liberation of CO_2 and H_2O by microbial activity (Fig. 1).

Composting is different from natural rotting. Natural rotting occurs in an unmanaged waste pile, sanitary landfill and/or open dump. However, composting is a controlled biochemical process. Different microbial populations mainly bacteria, actinobacteria, and fungi convert organic materials into humus-like substances during bioprocess. Microorganisms need food and energy during bioprocess. They use carbon as an energy source and nitrogen to build up cell structure, proteins, enzymes, and hormones. They take their necessary foods and nutrients from com-

Table 3 Factors affecting the composting of rice straw (Shafawati and Siddiquee 2013; Malińska and Zabochnicka-Świątek 2013)

Parameters	Reasonable range	Preferred range
Temperature (°C)	42–68	55–60
Carbon to nitrogen ratio (C:N)	20.1–30.1	25.1–30.1
Aeration (% of oxygen)	>5.0	>5.0
Moisture content (%)	45–70	50–60
Porosity (%)	30–60	30–36
pH	5.5–8.0	6.5–7.5
Particle size (diameter—cm)	0.5–5.0	0.5–2.5

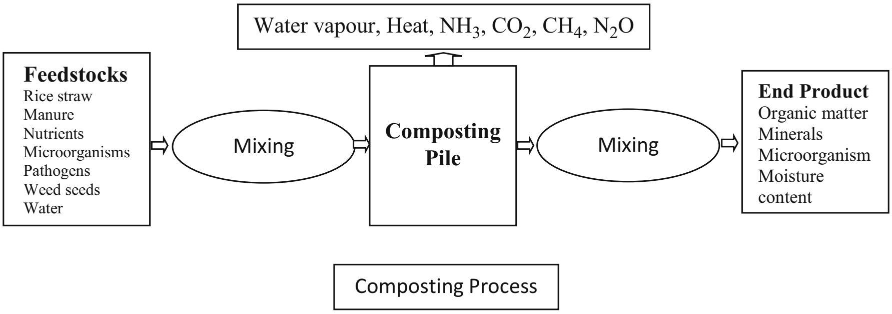

Fig. 1 Conventional composting process (British Columbia Agricultural Composting Handbook 1998)

plex organic substances. Nutrients released during the composting process remain in the compost as humus and the dead bodies of microorganisms (Zainudin et al. 2013; Qian et al. 2014; Vázquez et al. 2015).

Lignin shields cellulose, hemicelluloses, and other cell wall components in rice straw. Only a few microorganisms can cleave the lignin barrier. Lignocellulolytic fungi have an advantage in solid state bioconversion as they are filamentous and produce prolific spores. Mixed microbial cultures have higher influence on substrate colonization through resistance to contamination and increased enzyme production. Strain compatibility is another important determinants in mixed microbial consortium that influences the density, distribution, organization, and ecological balance of communities (Martínez-Sanz et al. 2014; Mishra and Malik 2014; Vázquez et al. 2015). Thus, a compatible microbial consortium perhaps plays an important role in the rapid bioconversion of rice straw.

Composting of rice straw with sewage sludge was evaluated in static piles with passive aeration for 90 days. Compost piles prepared with shredded rice straw reached the maximum temperatures remained above 55 °C revealed that rice straw and sewage sludge were compatible and shredding of straw was necessary to prepare a good blend for composting of these wastes and to guarantee quality compost in sanitation terms (Roca-Pérez et al. 2009).

Rice straw with different organic amendments and lignocellulolytic actinomycete strains of the genera *Micromonospora*, *Streptomyces*, and *Nocardioides* were composted for 3 months under aerobic condition. Results showed that thermally treated municipal sludge and actinomycetes accelerated the composting where bulk volume was reduced by 38.6–64 %, after 3 months, compared to 13.6 % in uninoculated control (Abdulla 2007). In another study, Mishra and Nain (2013) documented composting of rice straw amended with poultry manure or urea co-inoculation of *Cellulomonas cellulans* and *Phanerochaete chrysosporium* in perforated cemented pits for 3 months. Microbial activities reached the highest after second month of composting. After 3 months, the carbon content decreased, but nitrogen content increased. In addition, pH and EC of the end product was found to be within the desirable limits for agricultural use at the end of 3 months of composting.

A fungal consortium comprising of *A. niger* and *T. viride* was found to decompose rice straw amended with chicken manure significantly over control treatment where the C/N ratio was reduced to 19.5 from an initial value of 29.3 in 3 weeks of composting (Kausar et al. 2010, 2013). In another study, Raut et al. (2009) found that municipal solid waste amended with *P. chrysosporium* and *T. reesei* was composted within 9–12 days as indicated by the reduction of C/N ratio and enzyme activities.

A study was conducted to monitor the chemical changes during composting of rice straw and cattle dung, biogas slurry and a consortium of *A. awamorii*, *Paecilomyces fusisporus*, and *T. viride*. At day 90, maximum 17.4 %, dropping in organic C was observed in the treatment containing fungal consortium where C:N ratio of compostable material reduced from 73.7 to 16.6 %. At day 30, cellulase activity was increased from 88 to 252 mg reducing sugar kg^{-1} dry matter h^{-1}, xylanase activity was from 9 to 111 mg reducing sugar kg^{-1} dry matter h^{-1} in microbial amended treatment. Total humic substances were 121 mg g^{-1} and 127 mg g^{-1} compost in finished product amended with fungal consortium and cattle dung, respectively. Carbon dioxide evolution in finished product in cattle dung and fungal consortium amended treatment was 188 mg 100 g^{-1} and 174 mg 100 g^{-1} compost, respectively. About 81–87 % seeds of wheat and 78–86 % seeds of mustard were germinated in compost extract amended with fungal consortium and cattle dung showing their potentiality to be used in the composting of rice straw at large scale (Goyal and Sindhu 2011).

5 Role of Rice Straw Compost in Soil Health, Plant Growth, and Disease Suppression

Composts have been shown to improve soil organic matter, content, resistance against soil erosion, water holding capacity and the subsequent mineralization of soil, plant nutrients (Puppala et al. 2007; Hejduk et al. 2012). It increases soil fertility and contains plant growth promoting substances, e.g., vitamins, hormones, enzymes that enhance plant growth and development (Gutierrez-Miceli et al. 2007; Pramanik et al. 2007; Zaller 2007; Ievinsh 2011; Papathanasiou et al. 2012; Zhang et al. 2012). Composts promote plant root elongation and density, which improves soil aggregation (Daynes et al. 2013). The incorporation of composts in soil improved the retention of nutrients, including magnesium, copper, and iron as well as of nitrogen, phosphorus, potassium, and sequestered carbon (C) (Lehmann et al. 2003; Barrow 2012; Cheng et al. 2012; Borchard et al. 2012; Clough and Condron 2010; Clough et al. 2013; Farrell et al. 2014).

Composts have been used in controlling soil-borne pathogens for a long time now. Composts suppress soil borne diseases by complex interactions between biotic and abiotic factors (Borrero et al. 2004; Litterick et al. 2004; Rotenberg et al. 2007). Composts increase labile carbon pools and soil microbial activities in soils. The disease suppressive potential of composts depends on the level of maturity and the presence of antagonists (Scheuerell et al. 2005). Mature composts sustain biocontrol agents by providing all essential nutrients. On the other hand, immature composts do not support biocontrol agents. They contain pathogenic populations and negatively affect plant growth (Litterick et al. 2004; Trillas et al. 2006).

Composts induce plant disease resistance by increasing the biocontrol agents in the rhizosphere. Plant resistance is induced when biocontrol agents cross the certain threshold size in the rhizosphere. Once resistance is induced the populations may decline without affecting the plant resistance. Composts containing biocontrol agents including *Penicillium*, *Trichoderma*, *Aspergillus*, *Gliocladium*, and *Paenibacillus* antagonize the causal organism of damping-off, stem and root collar rot. The interactions in between the saprophytic microbes and the pathogens and/or the systemic and local resistance of composts are involved in this effect (Kavroulakis et al. 2005; Suárez-Estrella et al. 2007). Composts increase the resistance in chilli, tomato, cucumber, wheat, and barley against *Fusarium* wilt, *Pythium* root rot, anthracnose, and powdery mildew (Lashari et al. 2013; Cao et al. 2014; Verma et al. 2015; Yu et al. 2015).

Rice straw compost rich is in nitrogen, potassium and silicon (Belal and El-Mahrouk 2010). It enhances plant growth, development, and disease suppression in chilli cultivation (Siddiqui et al. 2008; Dukare et al. 2011; Kausar et al. 2014). Rice straw composts were used for chilli cultivation under glasshouse condition. Chilli seeds cv. Kulai were sowed in *Sclerotium rolfsii* challenged soil where microbial infused straw compost increased seed germination, seedling establishment, plant growth and suppressed development of foot rot disease compared to using commercial compost and fungicide Benomyl (Table 4). Use of 15 Mg ha^{-1} microbial infused rice straw compost yielded optimum seed germination (98.1 %), seedling establishment (96.8 %), and disease suppression (84.6 %) (Fig. 2).

Microbial fortified rice straw compost was applied with *Pyricularia oryzae* challenged inoculation at 14, 56, and 80 days after sowing for plant growth promotion, resistance, induction, and yield increment on rice variety M4 under greenhouse conditions. Microbe amended compost significantly increased plant biomass and productivity. Productive tiller number ($r = 0.96$), leaf area index ($r = 0.96$), area under disease progress curve ($r = -0.62$), and infected panicle ($r = -0.59$) were highly correlated with rice yield with *P. oryzae* inoculation at 80 days after sowing. Low productivity was found with *P. oryzae* infection at the later growth stage due to increase in panicle blast that caused deterioration of grain quality and resulting in severe yield loss (30.99 %) as compared to early infection at 14 days after sowing (Ng et al. 2012).

Siddiqui et al. (2008) compared the efficacy of *Trichoderma* fortified rice straw and empty fruit bunch of oil palm compost extracts on occurrence and morphophysiological growth of Choanephora wet rot of okra. They found shoot and tap root length, leaves per plant, and leaf area were significantly higher in

Table 4 Effect of rice straw compost on seed germination, seedling establishment, and dry matter accumulation on chilli in *Sclerotia rolfsii* infested and non-infested soil

	Seed germination (%)		Seedling establishment (%)		Dry weight	
Treatment	Non-infested	Infested	Non-infested	Infested	Non-infested	Infested
T1	88.1 d	23.1 d	85.0 c	16.2 d	0.8 d	0.4 d
T2	91.8 cd	26.8 d	89.3 bc	19.3 d	1.0 d	0.6 d
T3	94.3 ac	87.5 b	92.5 ab	84.3 b	3.0 b	1.7 b
T4	98.1 a	94.3 a	96.8 a	92.5 a	4.5 a	2.8 a
T5	93.1 bc	81.2 c	90.0 bc	75.0 c	2.5 bc	1.3 c
T6	95.6 ac	88.7 b	91.8 ac	83.7 b	3.4 b	2.2 b
T7	96.8 ab	93.7 a	94.3 ab	91.8 a	3.2 b	2.0 b

T1 = Untreated soil (control); T2 = Soil + basal fertilizer; T3 = Soil + basal fertilizer + 7.5 t/ha *microbial infused* rice straw compost; T4 = Soil + basal fertilizer + 15 t/ha *microbial infused* rice straw compost; T5 = Soil + basal fertilizer + 7.5 t/ha Best Flora compost (commercial); T6 = Soil + basal fertilizer + 15 t/ha Best Flora compost (commercial); T7 = Soil + basal fertilizer + Benomyl @ 0.55 kg/ha

Means within columns followed by the same letter are not significantly different, 5 % level of probability, least significant difference (LSD) test

Fig. 2 Effect of microbial infused rice straw compost on plant growth and disease incidence on chilli in *Sclerotia rolfsii* infested soil. (**a**) Chilli plants treated with 15 t/ha microbial infused rice straw compost; (**b**) Plants in control treatment; (**c**) Single plant from the treatment treated with 15 t/ha microbial infused rice straw compost; and (**d**) Single control treatment

rice straw compost extract treated plants than that of empty fruit bunch compost extract. Similarly, net photosynthetic rate and chlorophyll content were also higher in plant receiving Trichoderma-enriched straw compost extract with a 76.2 % reduction in Choanephora wet rot incidence compared with rest of the treatments.

Man and Ha (2006) found that rice straw compost in combination with 50 % NPK fertilizer increased yield of rice from 26.98 to 37.04 % in the dry season and from 33.45 to 48.08 % in wet season. They also found that after compost application pH value was from 4.60 to 6.74 in dry soil and from 6.38 to 6.83 in wet soil where pH was not toxic to plant growth.

Rice straw composts amended with rock phosphate and *A. niger*, *T. viride* and/or farmyard manure were applied as organic phosphate fertilizers on cowpea plants in pot experiments. All types of rice straw fertilizers were better than superphosphate fertilizer in providing the cowpea plants with phosphorus. *A. niger* and *T. viri*de inoculated rice straw composts provided the maximum amount of soluble phosphorus (1000 ppm). Cowpea plants receiving compost inoculated with farmyard manure, *A. niger* and *T. viride* resulted in maximum amount of phosphorus uptake (295 ppm). The highest numbers of phosphate dissolving fungi were found in rhizosphere soil treated with *A. niger* and *T. viride* composts, while the highest phosphate dissolving bacterial numbers were found in soil receiving farmyard manure and rice straw compost (Zayed and Abdel-Motaal 2005).

Composting of rice straw with poultry manure and oilseed rape cake and its effects on growth and yield of faba bean and soil properties was studied in pot experiments at Gifu University, Japan in 2001–2002. Compost was rich in organic matter and mineral nutrients with higher level of stability. The use of compost (20–200 g pot-1) increased total N, total C and CEC, decreased particle density and increased soil respiration rate. Application of compost at a rate of 20 g/pot significantly increased growth, yield, yield components, and total crude protein of faba bean (Abdelhamid et al. 2004).

6 Mechanisms of Disease Suppression

Composts serve as a potential alternative to chemical fungicides in controlling plant diseases. The biocontrol agents, metabolites, plant nutrients, and humic acids present in compost suppress diseases. The biocontrol agents compete for infection sites with the pathogens. They leave little spaces for pathogens to proliferate or to secrete secondary metabolites on the plant surface. They also directly parasitize plant pathogens (Bernard et al. 2012; Daguerre et al. 2014), produce different antibiotics which suppress plant pathogens and enhance natural plant defense responses (Souleymane et al. 2010).

In general, biocontrol mechanisms of composts are grouped into two classes. These include general and specific suppression. The biocontrol agents in composts induce the general suppression of phytopathogens such as *Pythium* and *Phytophthora* (Shen et al. 2013; Mehta et al. 2014). Propagules of these pathogens do not germinate in compost amended substrates due to the metabolic activity of biocontrol agents (Dukare et al. 2011; Cray et al. 2015). On the other hand, *Rhizoctonia* spp. which produce sclerotia are not controlled by the general suppression phenomenon. To control damping-off caused by *Rhizoctonia* spp. the presence of specific antagonists such as *Trichoderma* spp. is required. This type of biocontrol is termed as specific suppression (Hoitink and Boehm 1999; Trillas et al. 2006; Olson and Michael Benson 2007).

The antagonistic potential of microorganisms is based on four basic principles: competition for space and nutrients, direct parasitism, antibiosis, and the induction of systemic resistance in host plants. Compost nutrients serve an indirect role with the production of antibiotics, siderophores in phyllosphere or rhizosphere giving fungistatic or fungistasis effect on pathogens (Termorshuizen and Jeger 2008; Bonanomi et al. 2013). Biocontrol agents including bacteria (*Bacillus*, *Pseudomonads*), actinobacteria (*Streptomyces*, *Micromonospora*), and fungi (*Trichoderma*, *Gliocladium*) induce these mechanisms during plant disease suppression.

Fluorescent *Pseudomonads* are the most frequently used rhizobacteria which suppress the growth of pathogenic rhizosphere microflora (Singh et al. 2011; Ahemad and Kibret 2014). Production of antifungal metabolites such as antibiotics and siderophores-mediated iron competition are primary mechanisms of these bacteria to suppress diseases. Siderophores serve to chelate the ferric ion (Fe^{3+}) from the environment into microbial cells and reduce the iron availability to pathogens.

Nonpathogenic *F. oxysporum* suppress Fusarium wilt of tomato (McGovern 2015). Competition for nutrients is the major mechanism of this strain. They compete with pathogens for colonization to the root surface and tissues and induce systemic resistance in host plants (McGovern 2015). *Trichoderma* is an effective antagonist against Fusarium wilt diseases. Some *Trichoderma* isolates compete and colonize potential infection courts and others induce systemic resistance in plants (Marzano et al. 2013). *T. hamatum* isolated from compost was reported to suppress diseases caused by *F. oxysporum* (Shafawati and Siddiquee 2013).

T. viride, *T. virens*, *T. harzianum*, and *T. hamatum* have been used as antagonists against soil and seed-borne diseases, diseases in the phyllosphere and storage rots (Coventry et al. 2005; Siddiqui et al. 2008). The mycoparasitic activities of *Trichoderma* spp. include competition, antibiosis, and production of cell wall degrading enzymes or a combination of these activities. *Trichoderma* spp. produces non-volatile antibiotics that inhibit the hyphae of phytopathogen. When *Trichoderma* recognizes the host, it attaches itself to the host and either grows along the host hyphae or coils around them and secretes lytic enzymes such as chitinase and hydrolase. Subsequently, disorganization of host cell wall occurs, resulting in osmotic imbalance followed by intracellular disruption. It has been shown that chitinolytic enzymes isolated from *T. harzianum* inhibit spore germination and germ tube elongation in several plant pathogens (Viterbo et al. 2001).

7 Conclusions and Future Perspectives

Microbial composting reduces the bulk volume of rice straw, destroys pathogens, converts nitrogen from unstable ammonia to stable inorganic forms, avoids air pollution, and satisfies the fertilizer needs for agricultural use. Composting is highly dependent on C:N ratio, pH, temperature, moisture content, particle size, and the potential of microorganisms present in the substrates. Under natural conditions, composting of rice straw usually takes as long as 6 months, but inoculation with lignocellulolytic microbial consortium at optimized conditions could reduce the bioprocess only to 3–4 weeks as well as enhance the maturity of end product. Fortification with biocontrol agents further enhances rice straw compost as biofertilizer and bioprotectant. However, future composting experiments on industrial scale and trials of compost amendment soil on different crops and field conditions are suggested to ensure the consistency of the obtained results which will expand our current knowledge on the sustainable management of bulky rice straw more precisely.

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